Near-Neoclassical Transport & Enhanced Stability in Reversed Shear Plasmas in TFTR

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Motivation

Reversed central magnetic shear configurations are particularly attractive for advanced tokamak reactors

-- predicted improved confinement and stability
-- compatible with bootstrap current profile shape

Mounting experimental confirmation of the advantages of reversed magnetic shear from a number of machines.

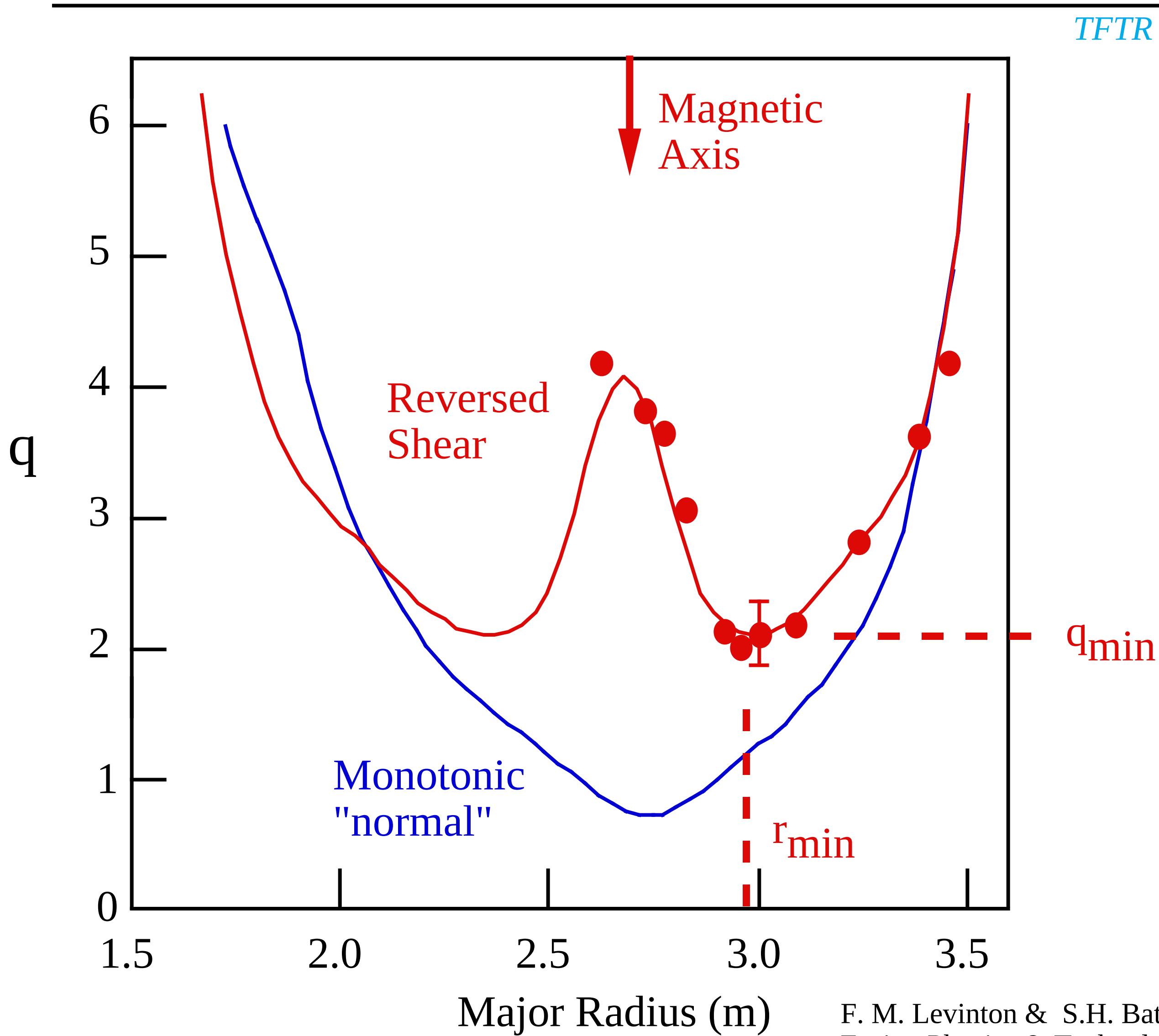
Reversed magnetic shear can:

- increase TFTR stability limits
- increase the reactivity of TFTR plasmas
- extend the range of physics studies for
  - -- α-physics
  - -- transport and stability of burning plasmas
  - -- integration of DT and advanced tokamak physics

Outline

- Formation
- Transport
- MHD Stability
- Future Directions

A Wide Range of Reversed Magnetic Shear Configurations Have Been Produced

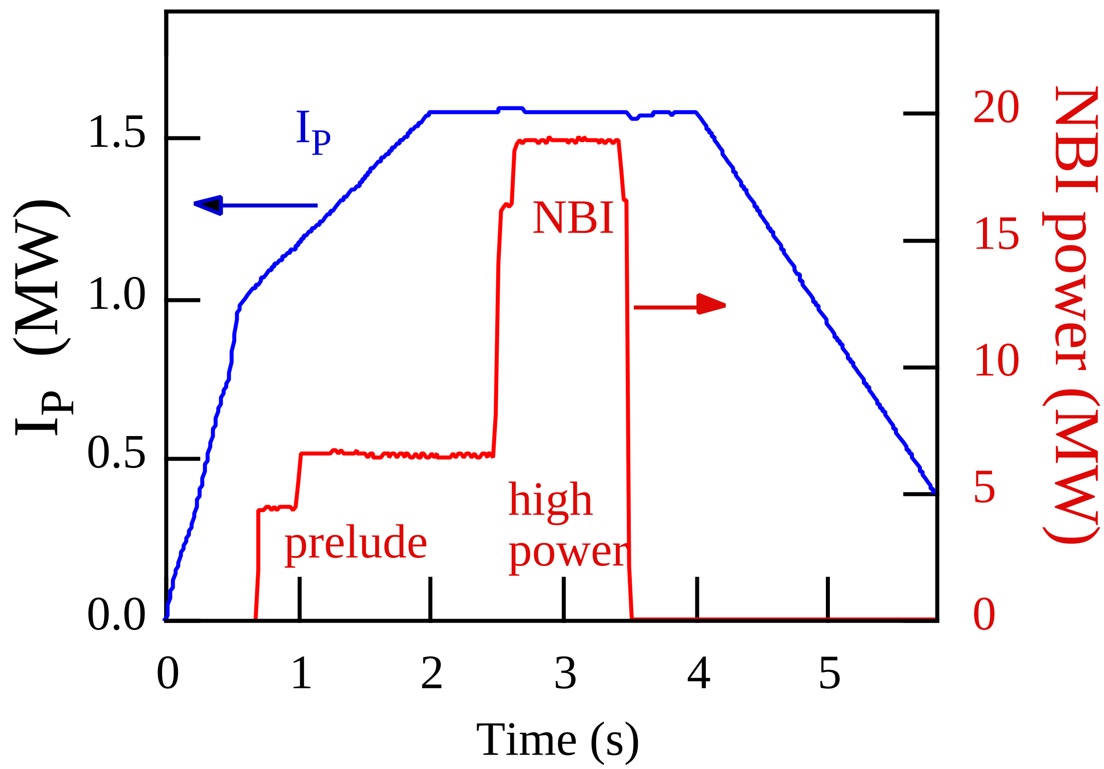


F. M. Levinton & S.H. Batha
Fusion Physics & Technology, Inc.

- Curves from VMEC free-boundary fit to MSE, magnetics data, and kinetic pressure profile
- Have obtained $1.8 \leq q_{min} \leq 3.3$ so far, $r_{min}/a \leq 0.5$ during I_P flat-top
- Configuration is reliably obtainable, routinely available.

Reversed Shear made by NB Heating & CD during I_P Ramp

TFTR



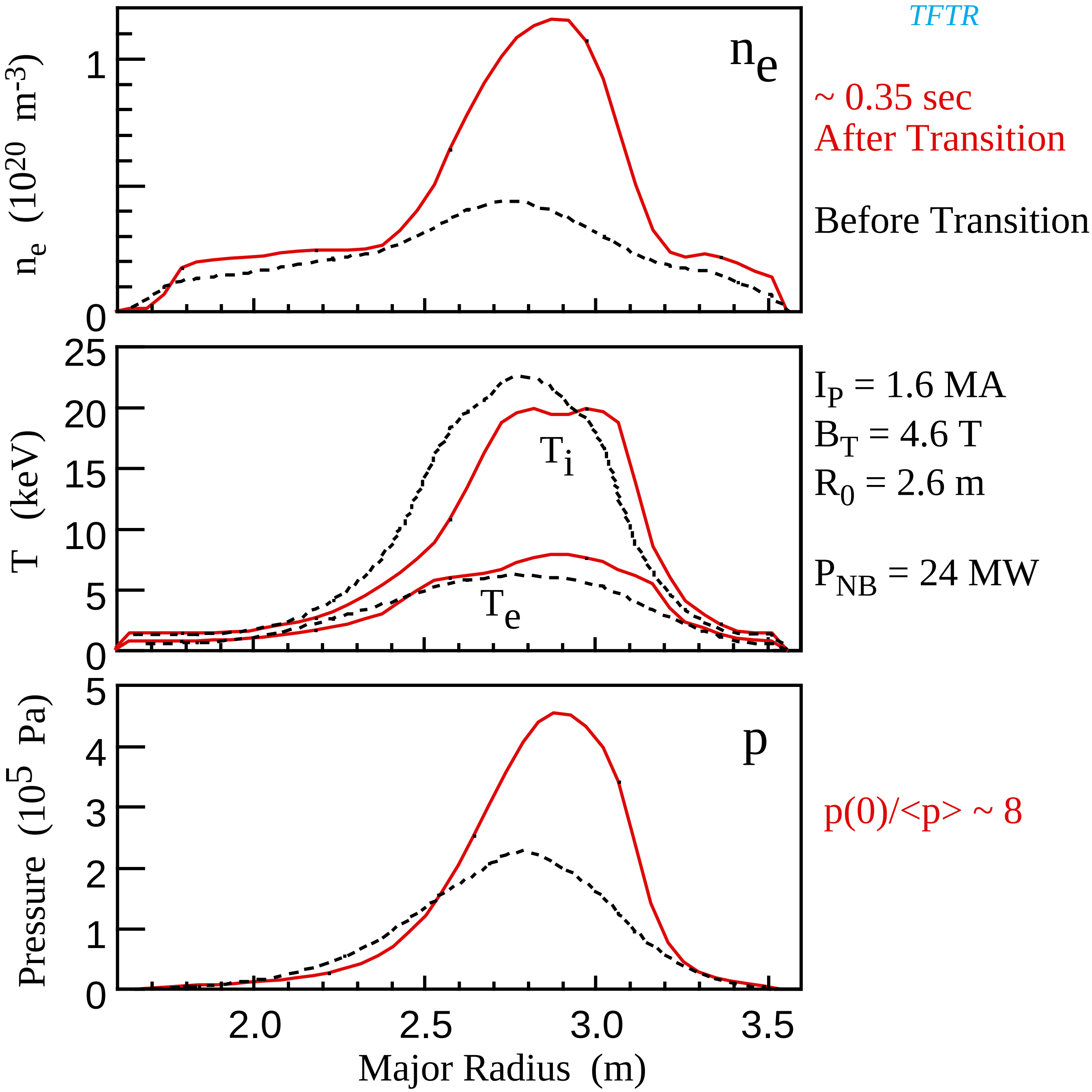
- Plasma is initiated at full size
  -- force current to diffuse maximum distance

- Scenario is robust, reproducible

- q_{min}, r_{min}, and q(0) can be controlled by the prelude NBI timing, co/counter-mix, the I_P ramp-rate and final I_P.

see S. Batha, 2F.02

Core Confinement is Strongly Improved after Transition to ERS



- Observed p(0)/<p> range from ~ 6.5 to ~ 8

- L_{pi} ~ ion banana width due to high central q
  ion orbit squeezing effects

- Calculated bootstrap current ~80% of total I_P

Two Confinement Regimes Observed with Reversed Shear

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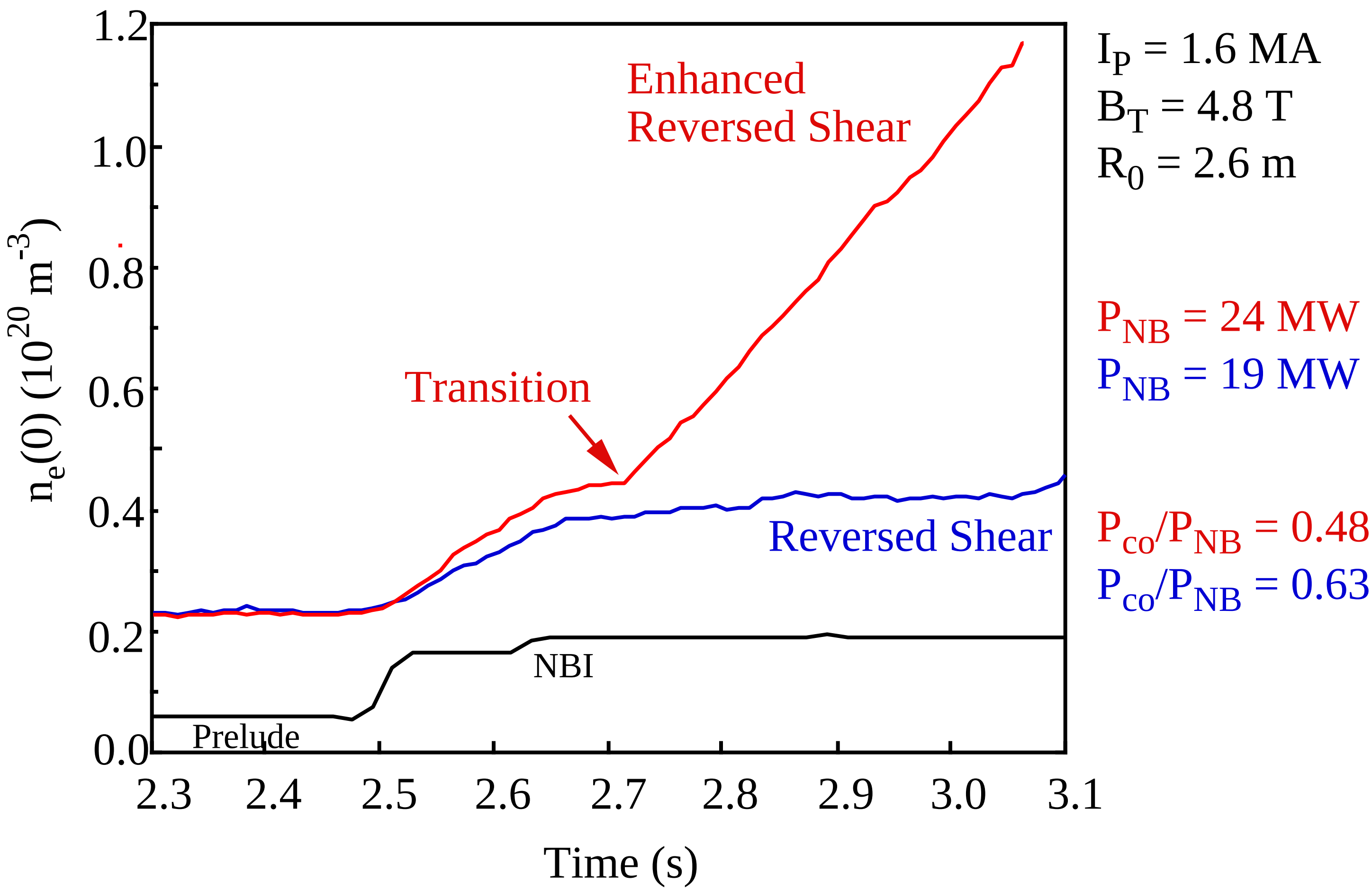
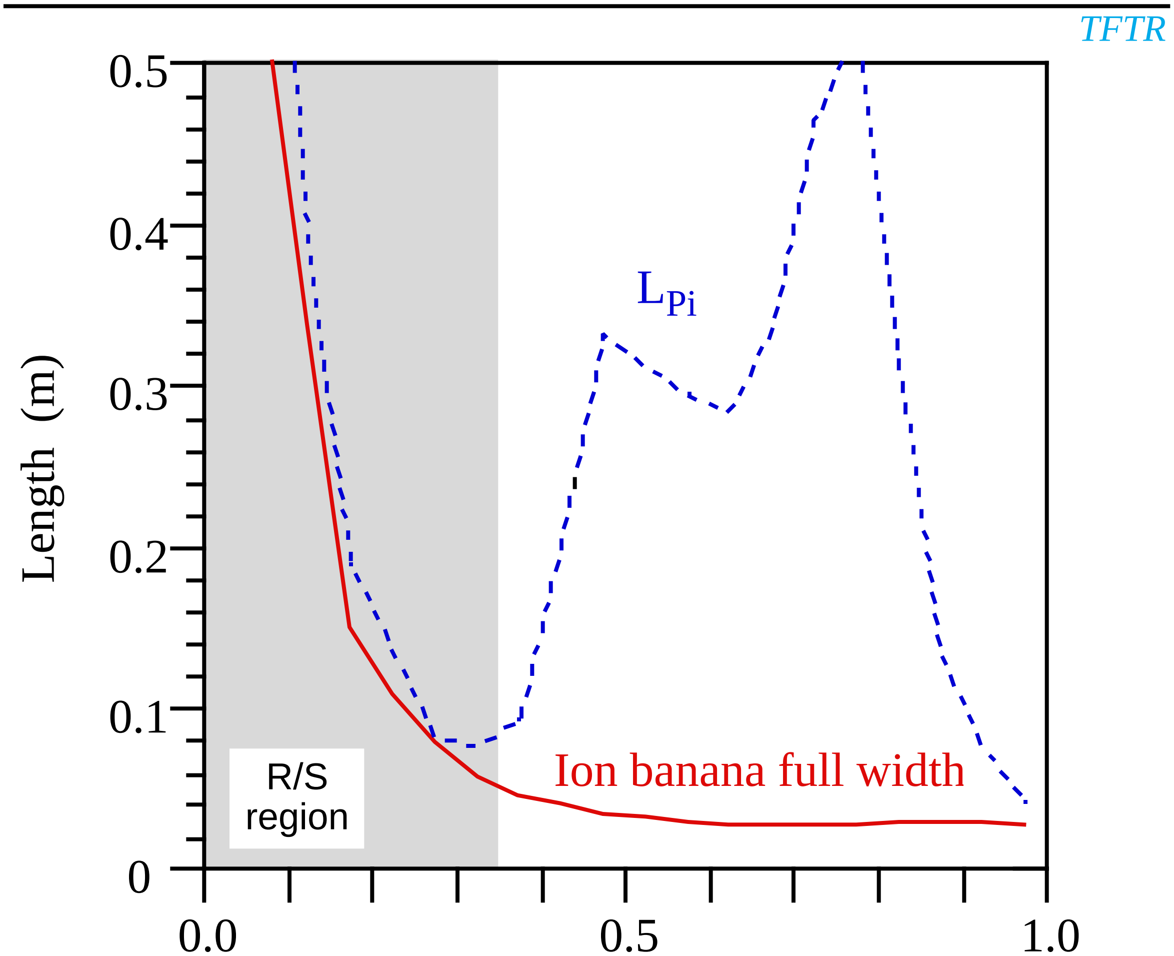


- Two confinement regimes observed with reversed shear:
  - (A) similar to supershots, convection dominated core, low χ_i, χ_e
  - (B) sudden transition to reduced particle transport and thermal transport ERS mode (Enhanced Reversed Shear)
- Transition appears to require balanced NBI > 16 MW
  - may have dependence on co/ctr mix of NBI
  - may have dependence on q_{min} or r_{min}

$\chi_i << \chi_i^{neo}$ may be due to L_{Pi} ~ Banana Width !



Likely indicates that ion orbit squeezing is important!

Improved Neoclassical calculations under development:

- orbit squeezing effects via recent papers by Shaing and Hazeltine; Hinton and Kim

  modification of Hirshman-Sigmar equations

- comparison with Full Torus Gyrokinetic Neoclassical Simulation (Z. Lin, W. Tang, W. Lee)

The Transition Threshold is Not Just a Function of Power

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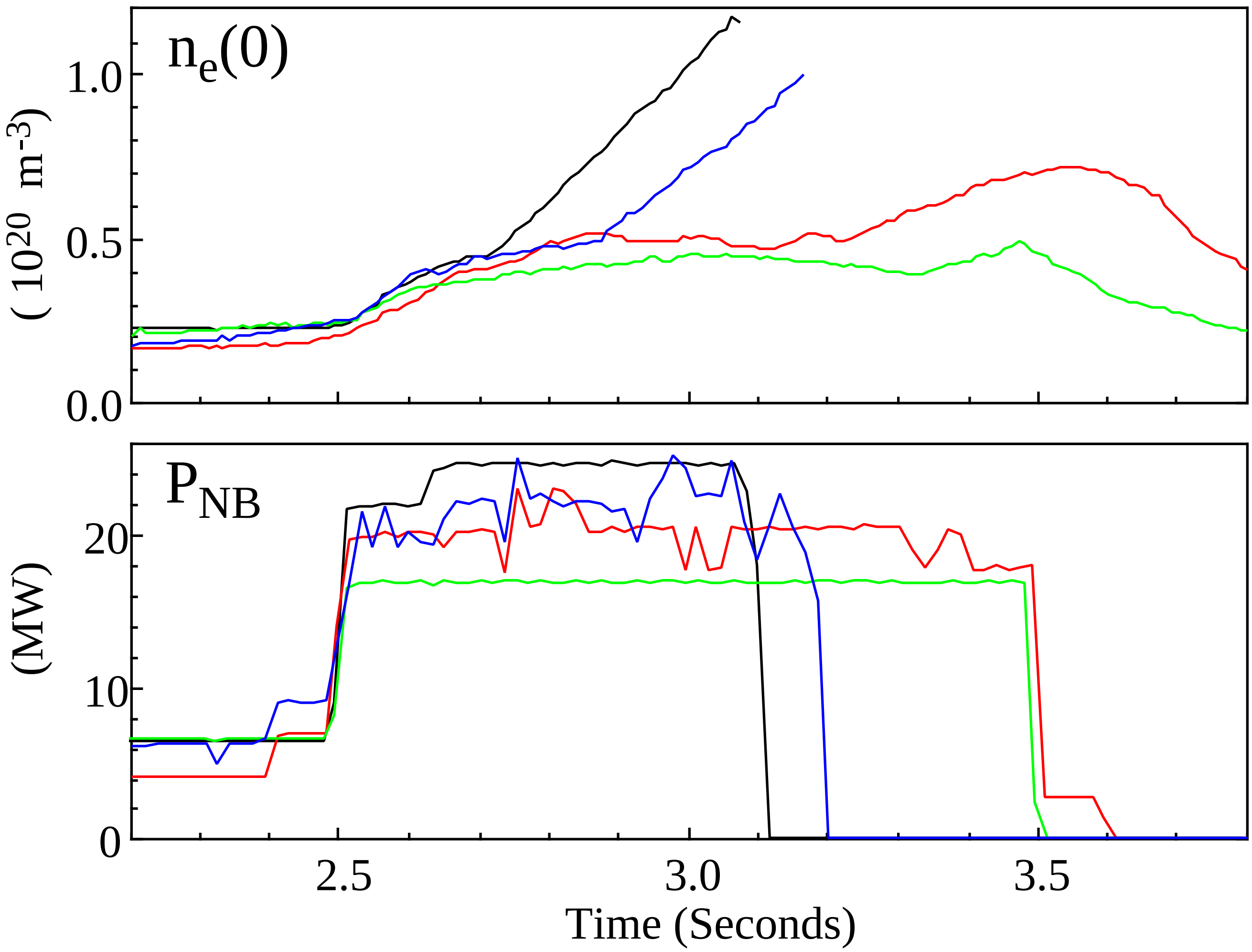

- All cases have near-balanced injection in high-power phase
- Lower power correlates with later transition
  perhaps due to lower q_{min}?
- Lowest power transition observed: P_{NB} = 16MW

Electron Particle Loss is a Small Fraction of the Fueling inside Reversal Surface

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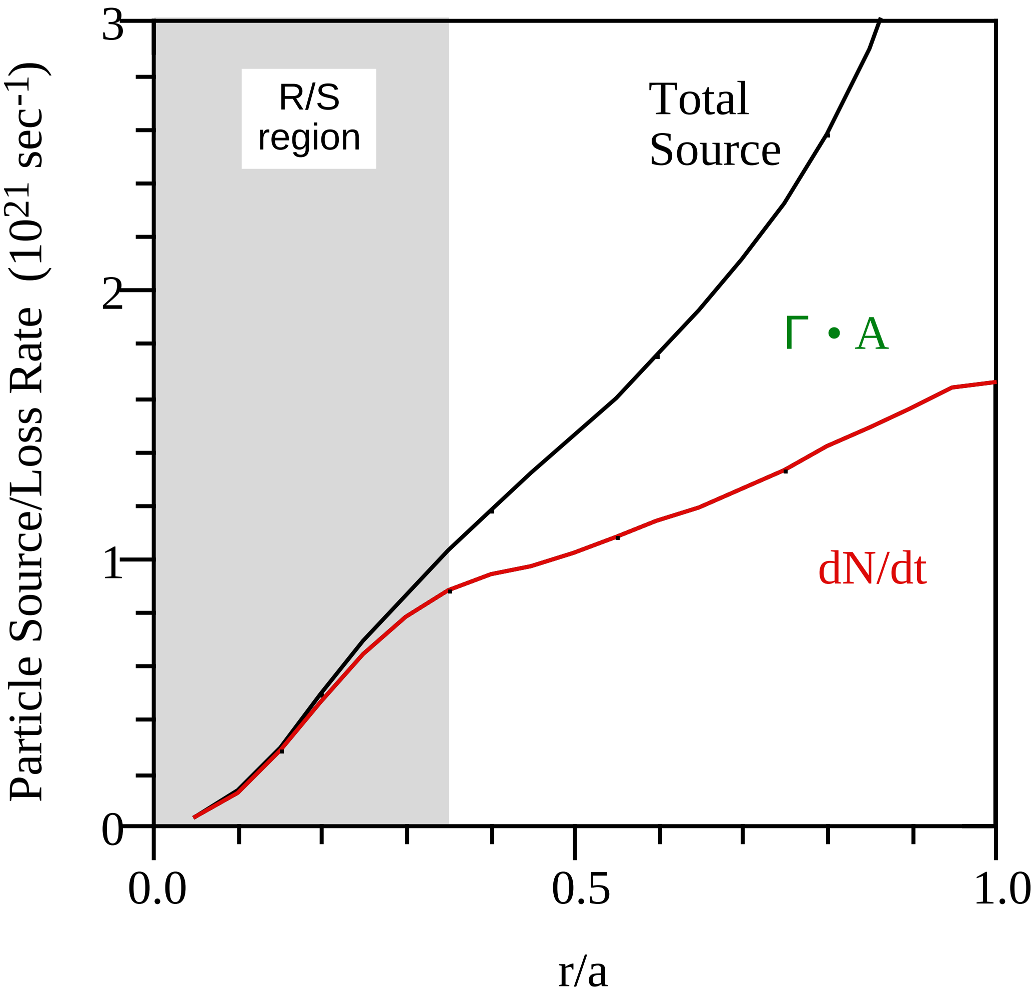
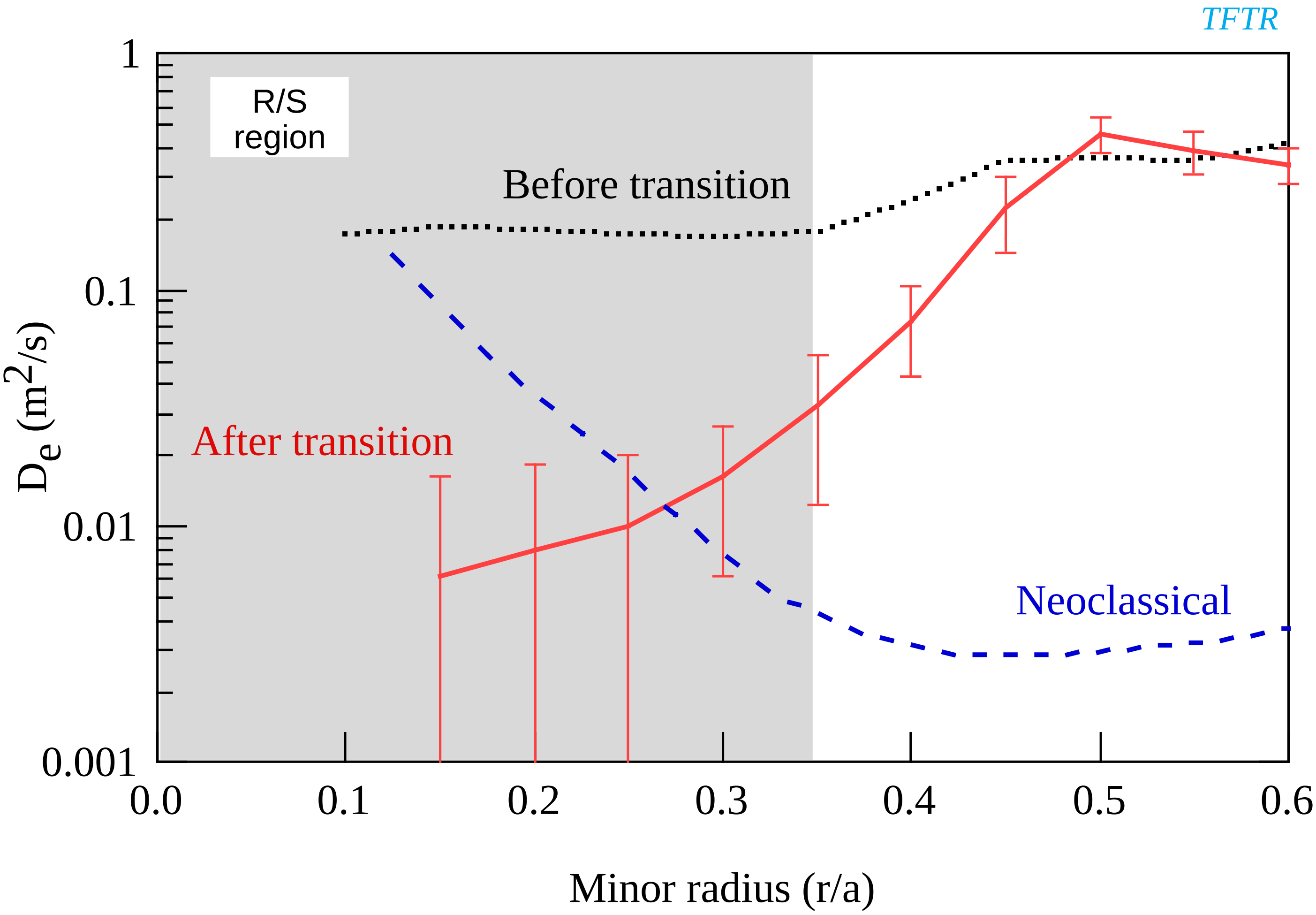


- Volume integrated electron continuity equation terms

  Indicates sources inside a flux surface and losses through a flux surface

- Source is dominated by beam fueling inside r/a ~ 0.9
  Wall source magnitude is measured by H_α array

D_e is Sharply Reduced after Transition



- $\Gamma \equiv -D \quad n$ flux balance "effective" diffusivity
- full neoclassical flux calculation including off-diagonal terms (Houlberg, Shaing, & Hirshman)
- low diffusivity or large pinch?

Ion Energy Loss is a Small Fraction of the Heating Power

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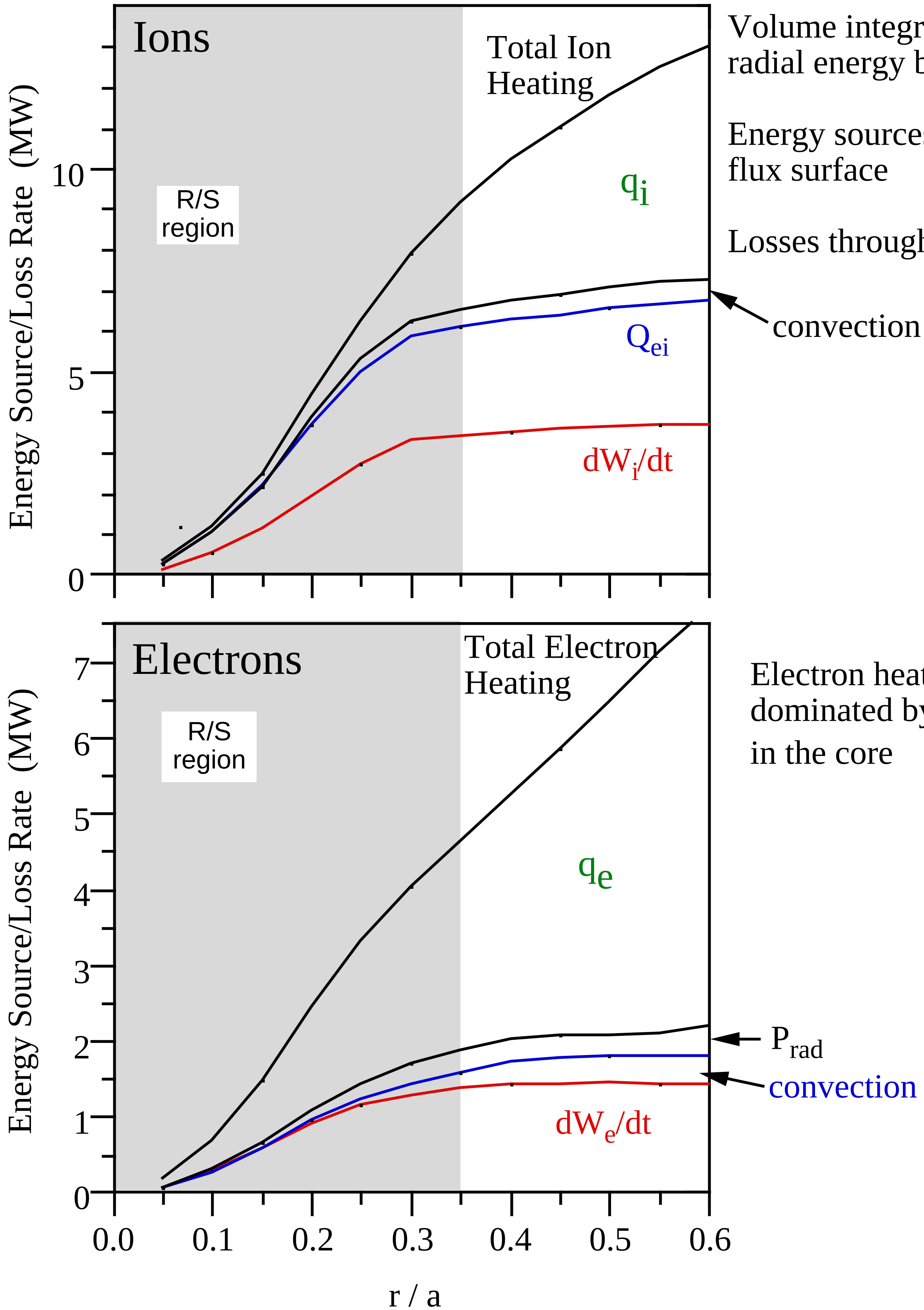

Volume integrated radial energy balances.

Energy sources inside a flux surface

Losses through a surface.

Electron heating is dominated by Q_{ei} in the core

χ_i is Sharply Reduced after Transition to below neoclassical level

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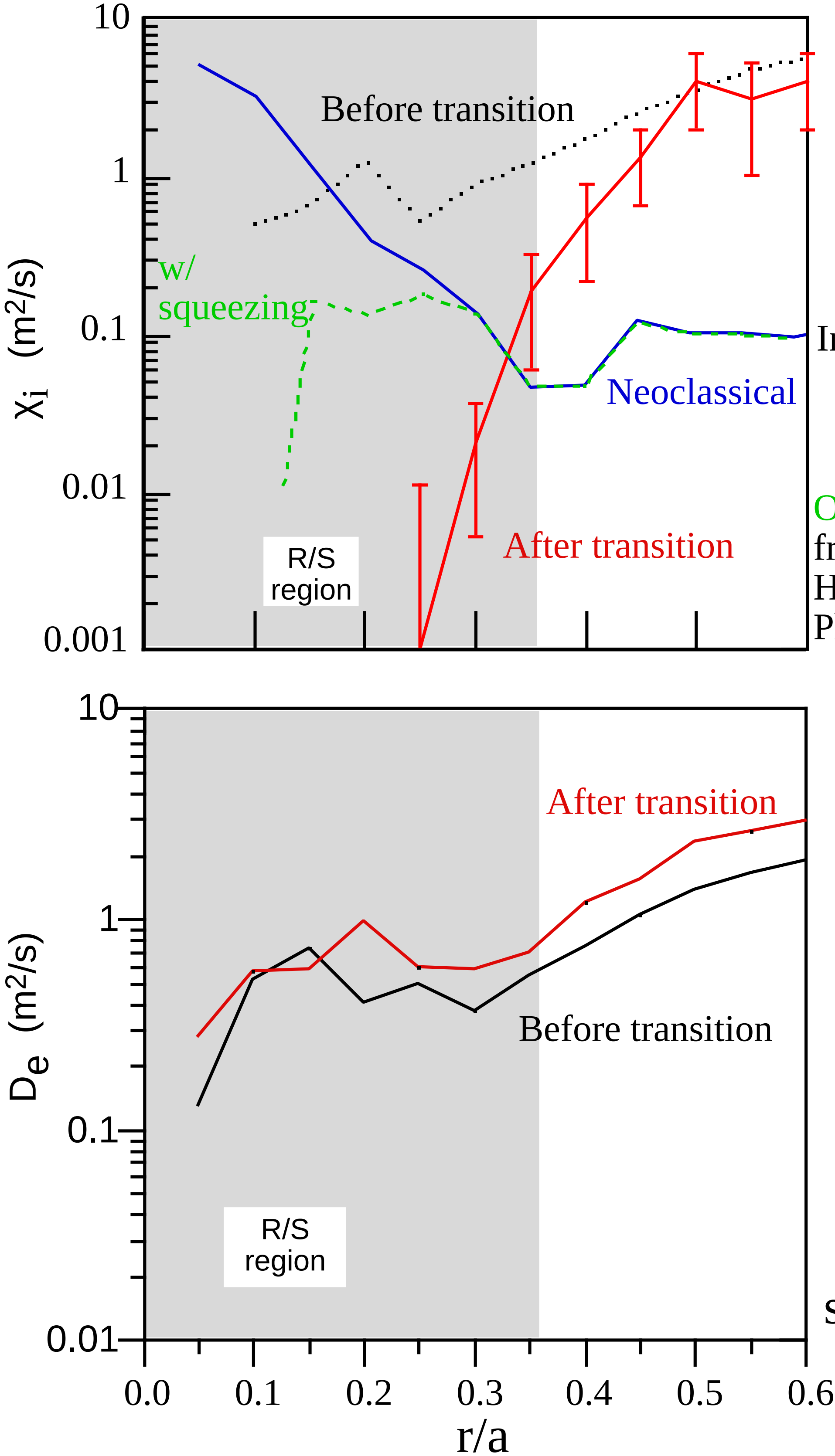


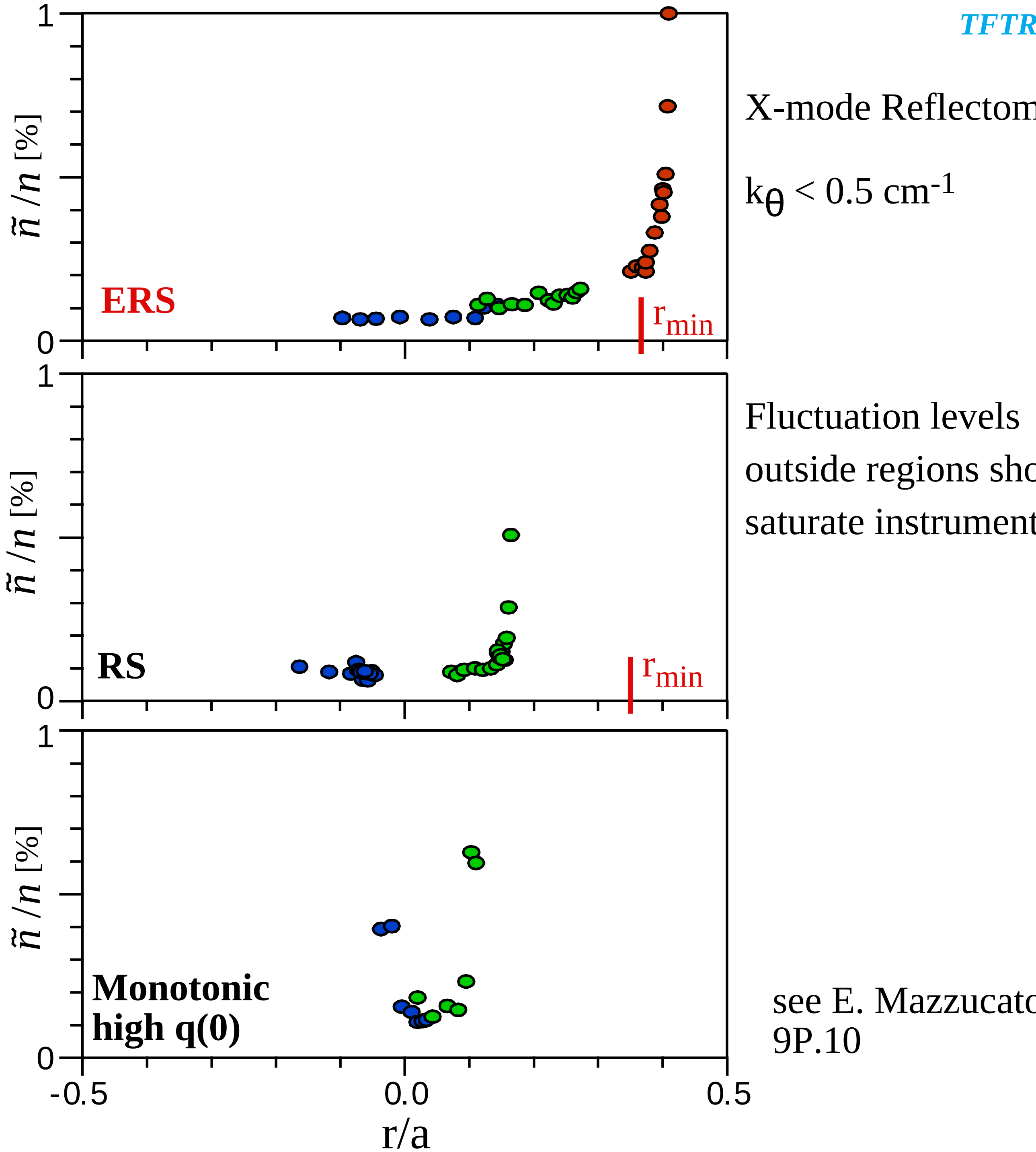
Includes off-diagonal terms

Orbit squeezing effects from Shaing, Hsu, and Hazeltine, Phys. Plasmas 1, 3365 (94)

Q_{ei} ?

see Levinton 9P.05

Core Turbulence Dramatically Reduced in ERS



X-mode Reflectometer

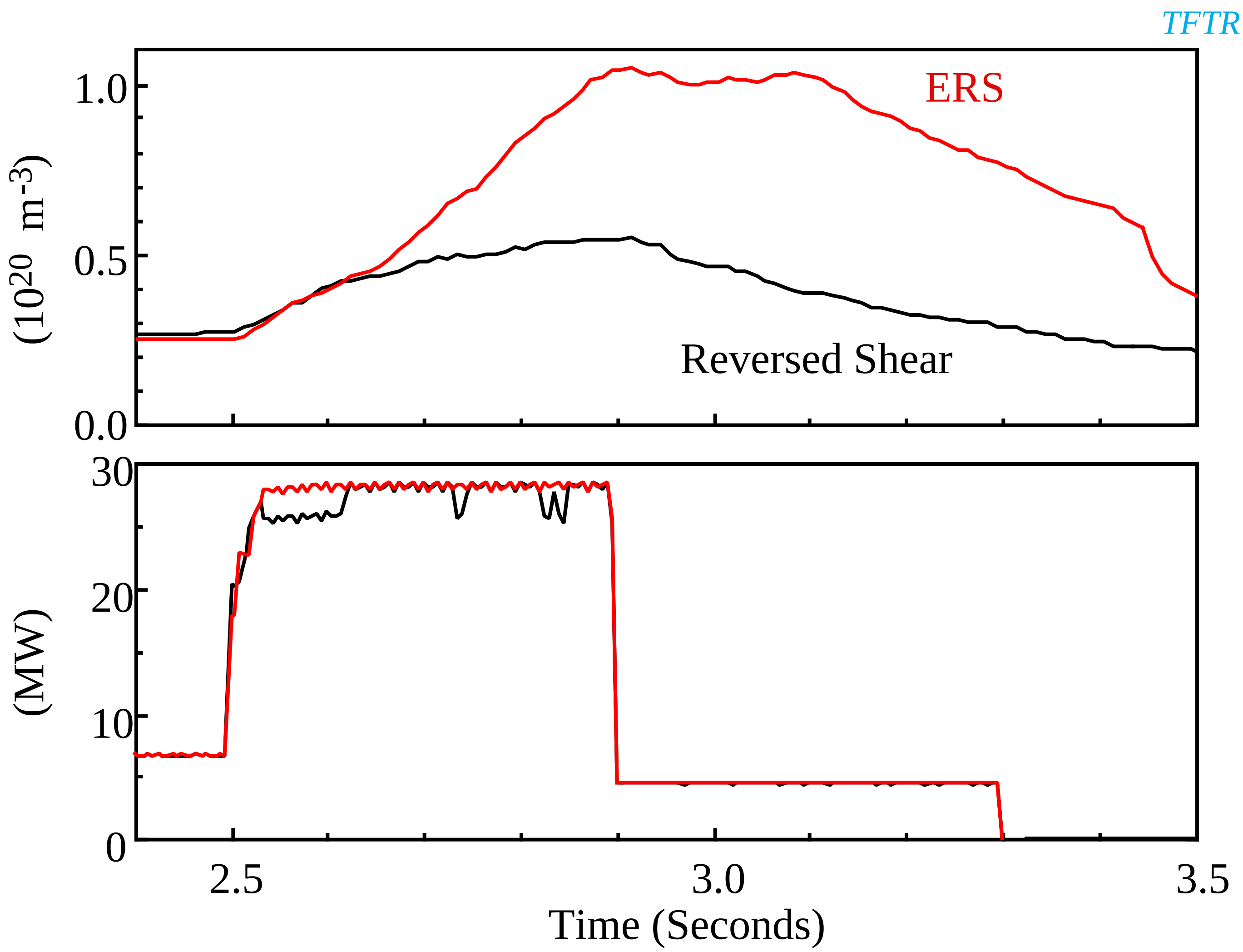
$k_\theta < 0.5\ cm^{-1}$

Fluctuation levels outside regions shown saturate instrument.

see E. Mazzucato 9P.10

- change in fluctuation profile appears coincident with transition
- preliminary BES analysis indicates core fluctuations levels are reduced to ≤ 0.2%, substantially less than with monotonic q(r).

Density Sustainment after High Power Phase Confirms Low D_e



- High central density can be maintainedwith ~5 MW of NBI
- After step down of P_{NB}, density outside r_{min} decays density peaking rises
- Reverse transition at ~3.1 sec ?

Hydrogenic transport is reduced in ERS

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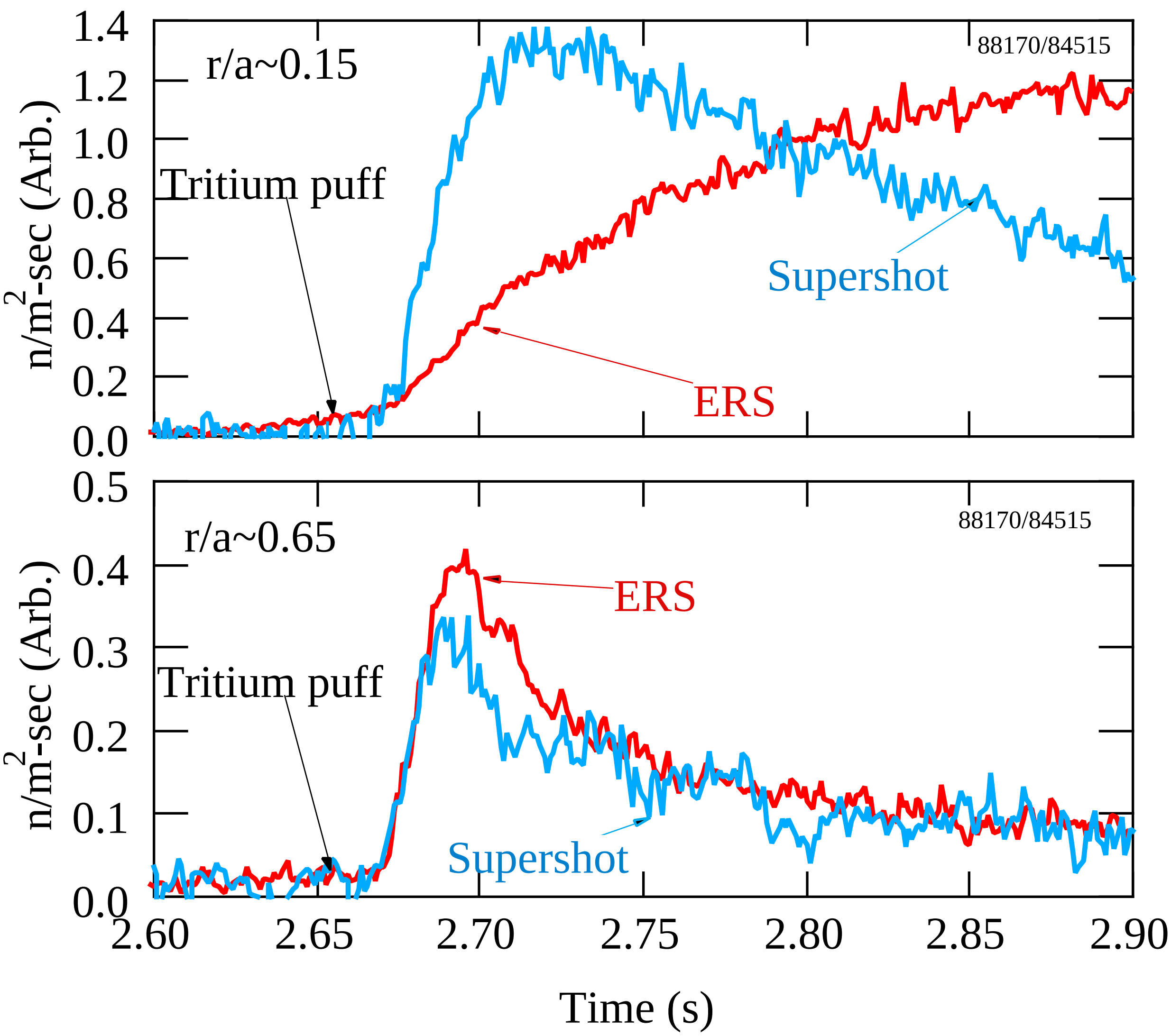

- Small Tritium puff in conjunction with neutron collimator measurements is used to study hydrogenic transport

- Core ion diffusivity is reduced in ERS, but similar outside reversed shear region.

Core Hydrogenic Diffusivity is Significantly Reduced in ERS Plasmas

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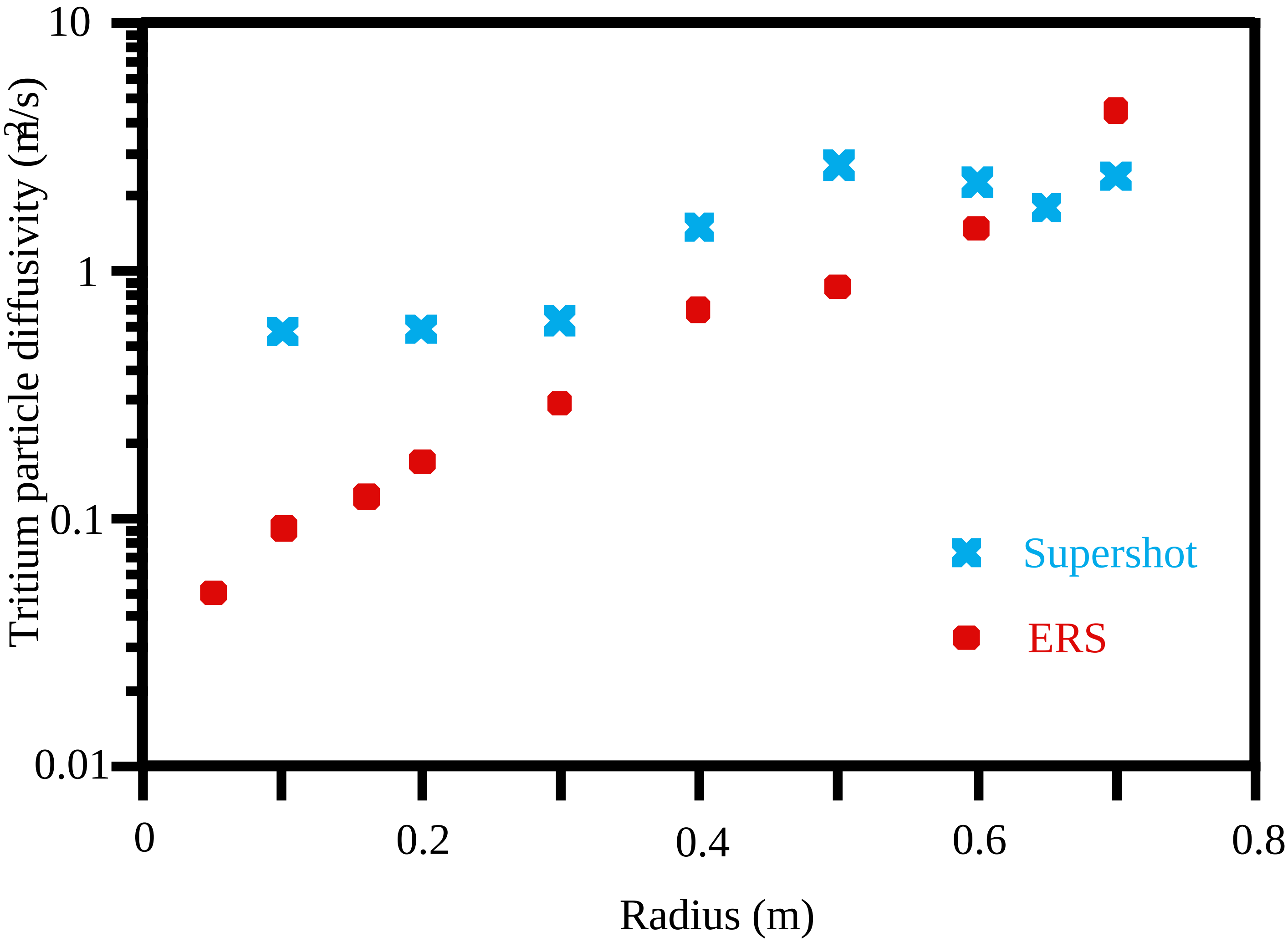
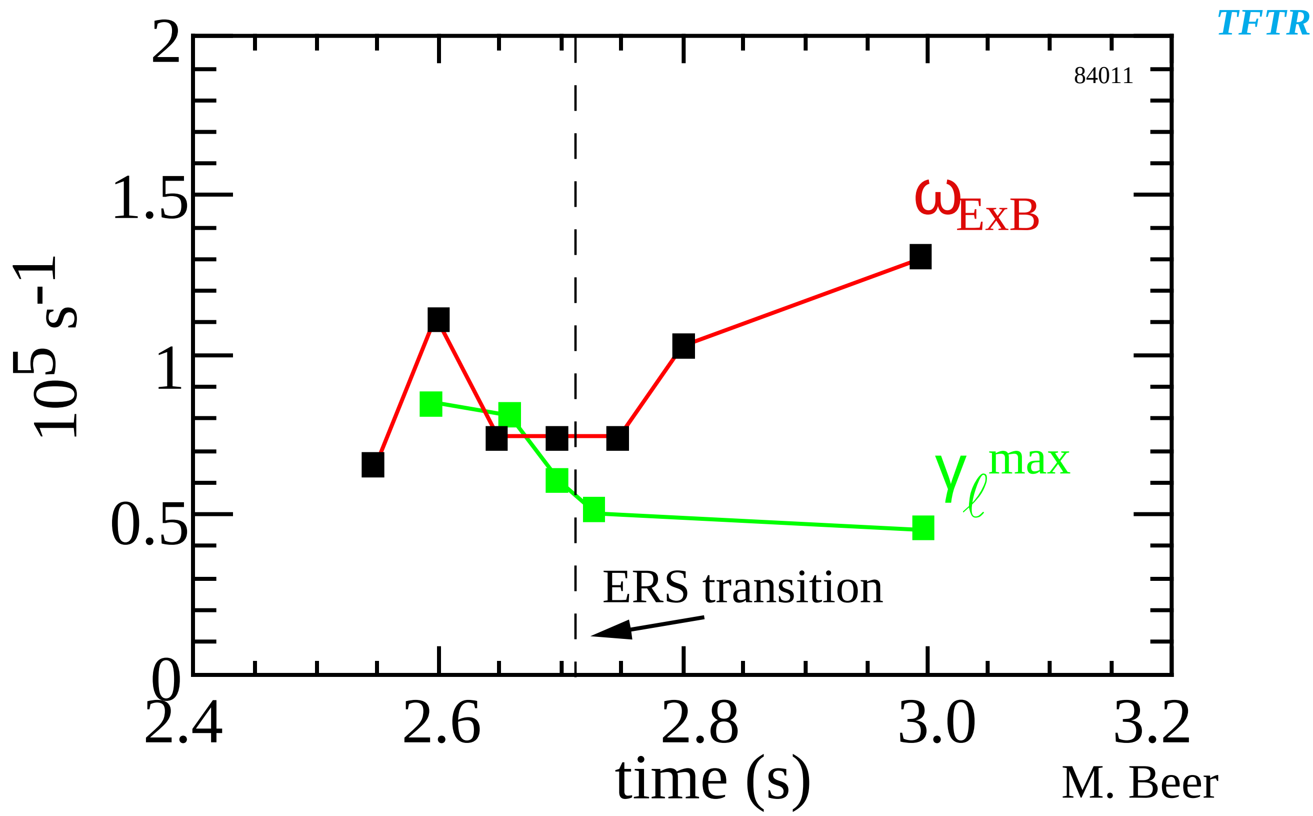


- Tritium transport determined from response of 12 channel neutron collimator to a tritium gas puff.

- For r < 0.6 m, convective velocity consistent with neoclassical theory.

- In ERS mode, particle flux in RS region is consistent with neoclassical predictions.

Possible Transition Mechanism: p driven increase of shearing rates and decrease of instability growth rates



1. ExB flow shear stabilization, generated by p (Synakowski, 2F12; Diamond 7Q21)

2. Increase in fraction of trapped particles with favorable drift precession from high $\alpha = -q^2 Rd\beta/dr$ due to strong Shafranov shift (M. Beer, 4Q08)

3. Peaking of density profile decreases ITG drive (S. Parker, 8IB3 and G. Rewoldt, 9P04)

Z_{eff} drops during ERS

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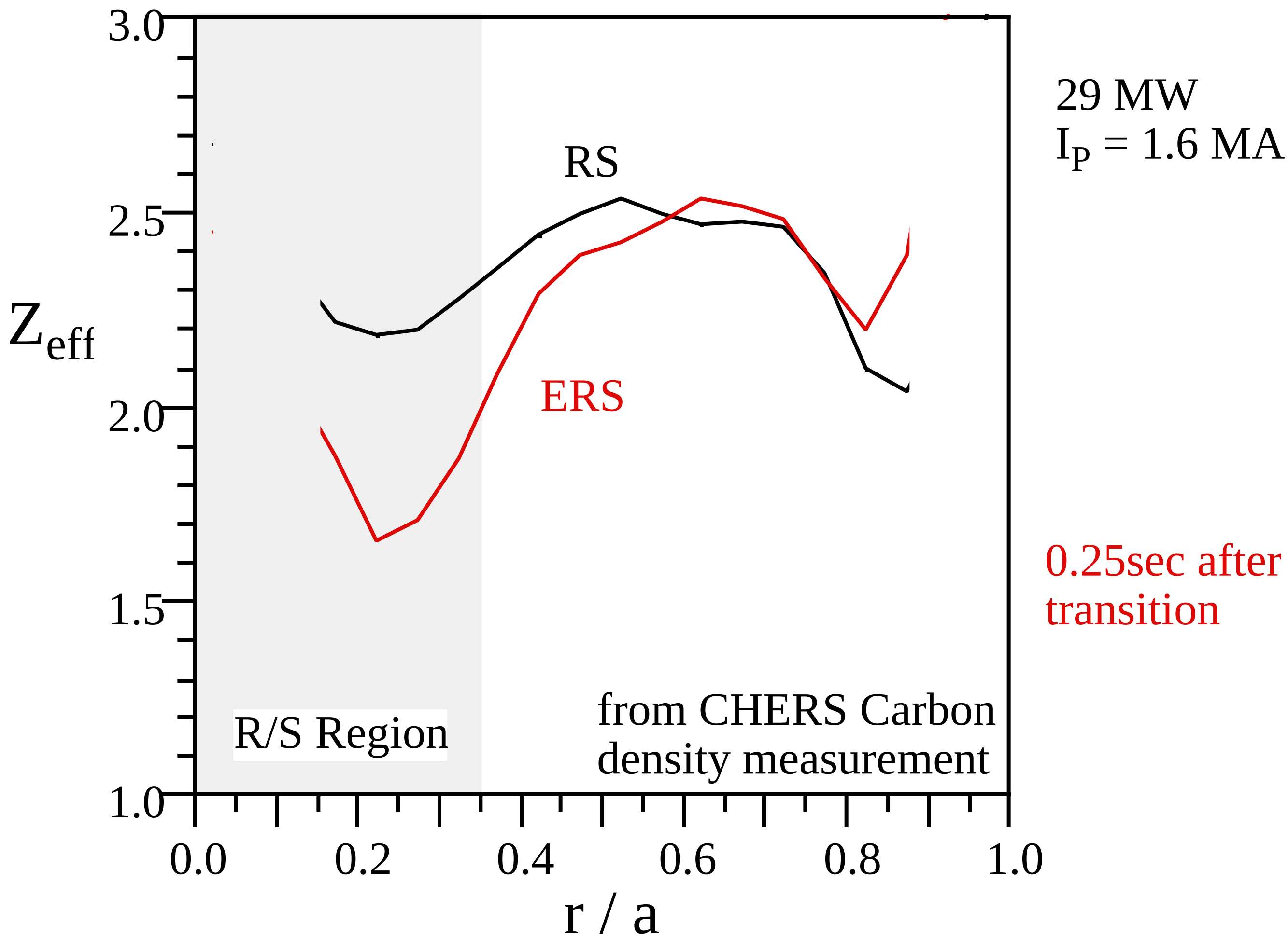

- Consistent with variation observed via Abel-inverted tangential visible-bremstrahlung array

  -- see A. Ramsey, 9P.38

- Nonlinear gyrofluid simulations indicate that residual fluctuations may drive outward carbon flux that balances neoclassical pinch

  -- see M. Beer, 4Q.08

RS Plasmas are Robustly Stable to High-n Modes in Plasma Core

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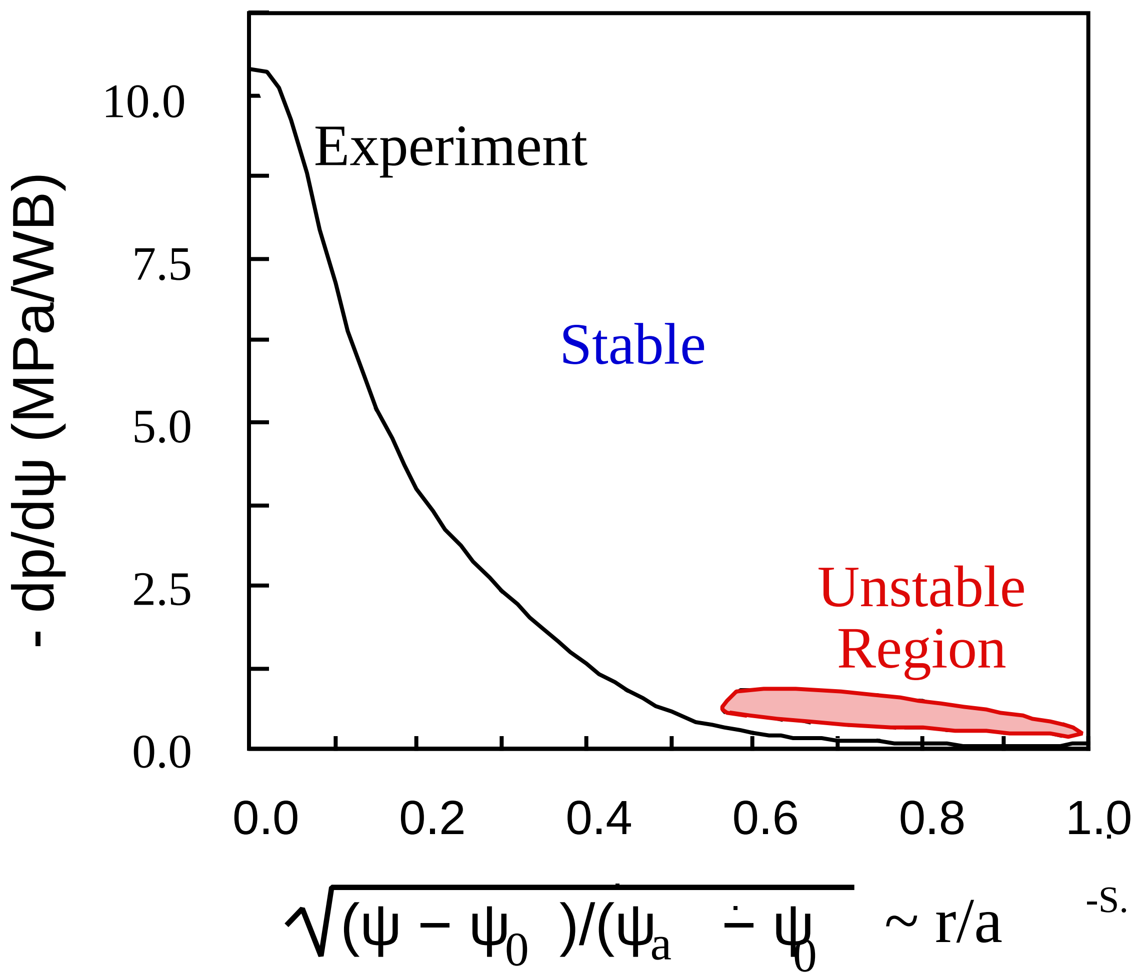


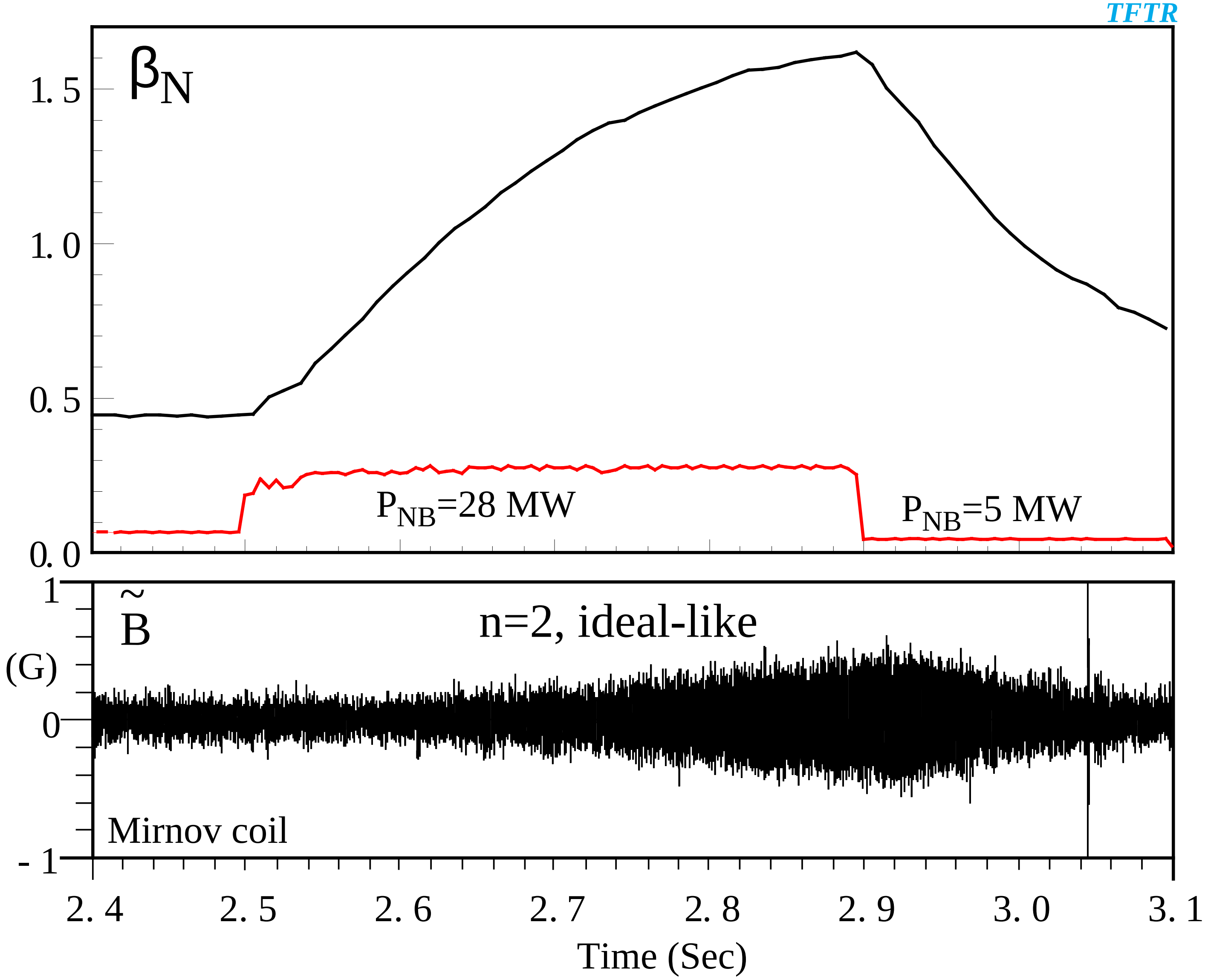
-S. Sabbagh

- Margin against high-n ballooning > factor of 2 at all radii. Robustly stable in core.

- This robust stability region extends to 80% of minor radius in some plasmas.

- Due to profile differences, some ERS plasmas can be near the ballooning limit outside r_{min}

Observed Saturated MHD Activity is Benign



- Observed on both RS and ERS plasmas
  No ERS specific MHD activity has been observed.

- May be resistive-kink mode? -- see T. Hender 9P.07

- No tearing-like MHD activity observed in plasma core.
No sign of neoclassical tearing modes observed with monotonic q(r).

- Off-axis "sawteeth" are observed after the high-power phase, with m/n = 2/1 precursors.

Disruption Precurser in Reversed Shear is n=1 Ideal-like Mode

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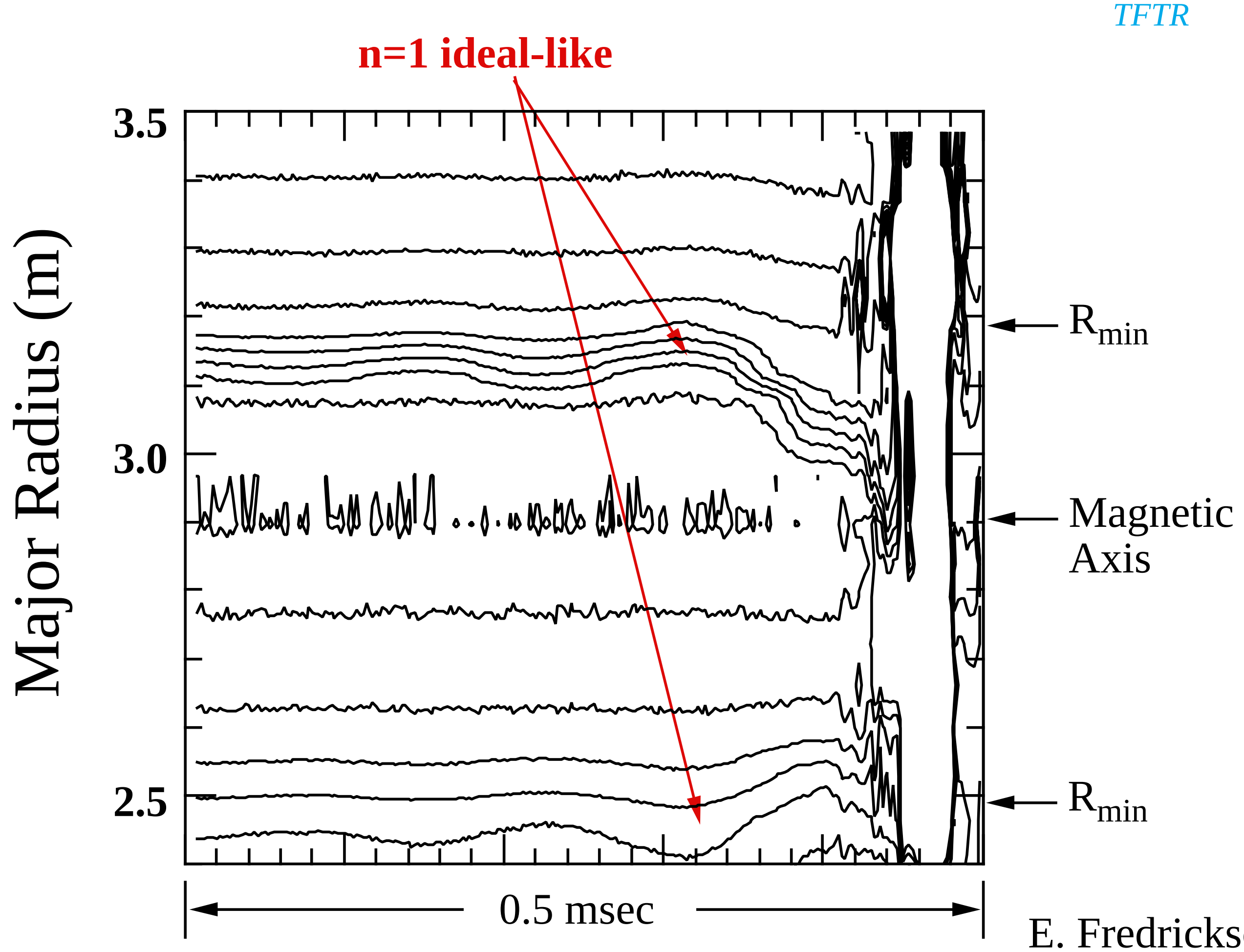


E. Fredrickson
Z. Chang

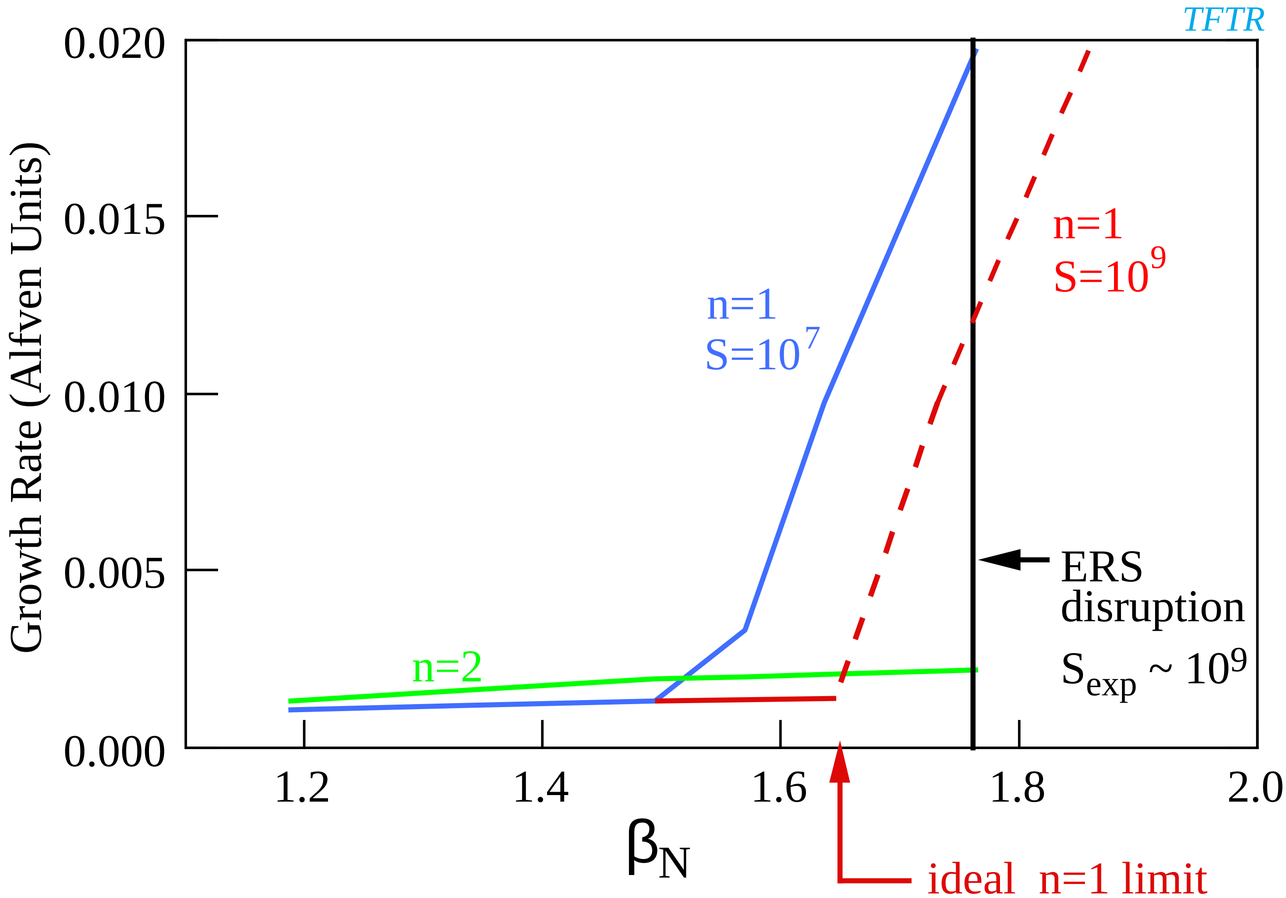
- Measured T_e evolution from ECE polychromator
  Similar measurements by reflectometer

- Disruption occured with
  $\beta_N^* = 3.5$, $\beta_N = 1.7$, $\beta(0) = 5.4$ %

- Maximum achieved with ERS:
  $\beta_N^* = 3.8$, $\beta_N = 2.0$, without disruption

In contrast, for monotonic q(r) and similar pressure profiles, the β_N limit is observed to be ~ 1.3 .

Theory: Stability is limited by *n*=1 Infernal Mode



• PEST calculates n=1 infernal mode becomes unstable at approximate β_N of disruption.

• Resistive stability agrees with ideal calculation at experimental Lundquist number $S \sim 10^9$.

• Resistive calculation indicates weak persistent n=2 and n=1 modes, observed in experiment.

-- see: T. Hender 9P.07; J. Manickam 9P.08;
M. Phillips 9Q.02; M. Hughes 9Q.01

Future Directions

- Optimization and control of MHD stability

  -- Theory predicts increased β_N* limits for increased r_{min}

  -- Need to control q-profile evolution to avoid unstable equilibria at high β (e.g. ~ integral q_{min})

- Understand transition and transport in new regime

  -- scaling of transition and transport
  -- control of barrier location
  -- ash transport

- Integrate DT and Advanced Tokamak physics

  -- α heating dynamics and profile modifications
  -- α stability with reversed shear

20 MW of Fusion Power is a Reasonable Goal

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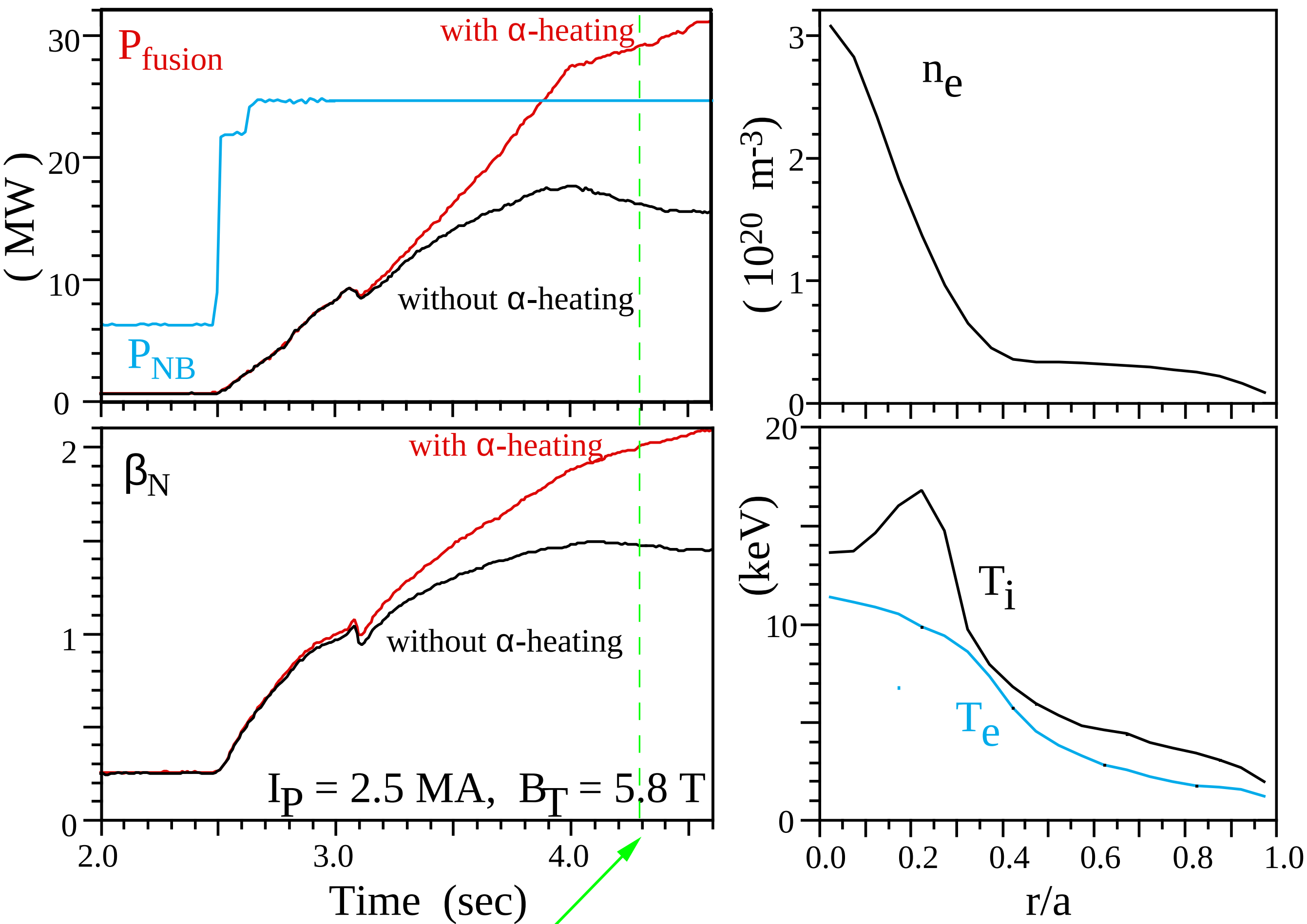

- β_N=2 calculated stable for all *n* (PEST) in this regime, and achieved experimentally

- Final n_e profile from equilibrium solution using observed D_e (with floor) T_e, T_i and equilibrium evolved using observed χ_e, χ_i (with floor), Z_{eff}=1.5

- Temperatures do not come to steady state! Q(0) > 5 when Q(a) ~ 1

CAUTION: this extrapolation is based on empirical transport coefficients in a new confinement regime, with no scaling information available.

Conclusions

TFTR

- Reversed magnetic shear configurations can be easily produced and studied in present experiments

- The new ERS regime offers
  - -- extremely low core transport and turbulence
  - -- new insight into the causes and limits of transport, mechanisms for transport barriers
  - -- new possibilities for reactor design:
    Low D_e: pellet or low-energy beam fueling?
    Low χ_i: α-channeling? advanced fuels?

- Reversed magnetic shear configurations have higher stability limits that monotonic q-profiles for similar pressure profiles

- Reversed shear and ERS provide a path for TFTR to explore strong alpha-heating and its interaction with advanced tokamak configurations.